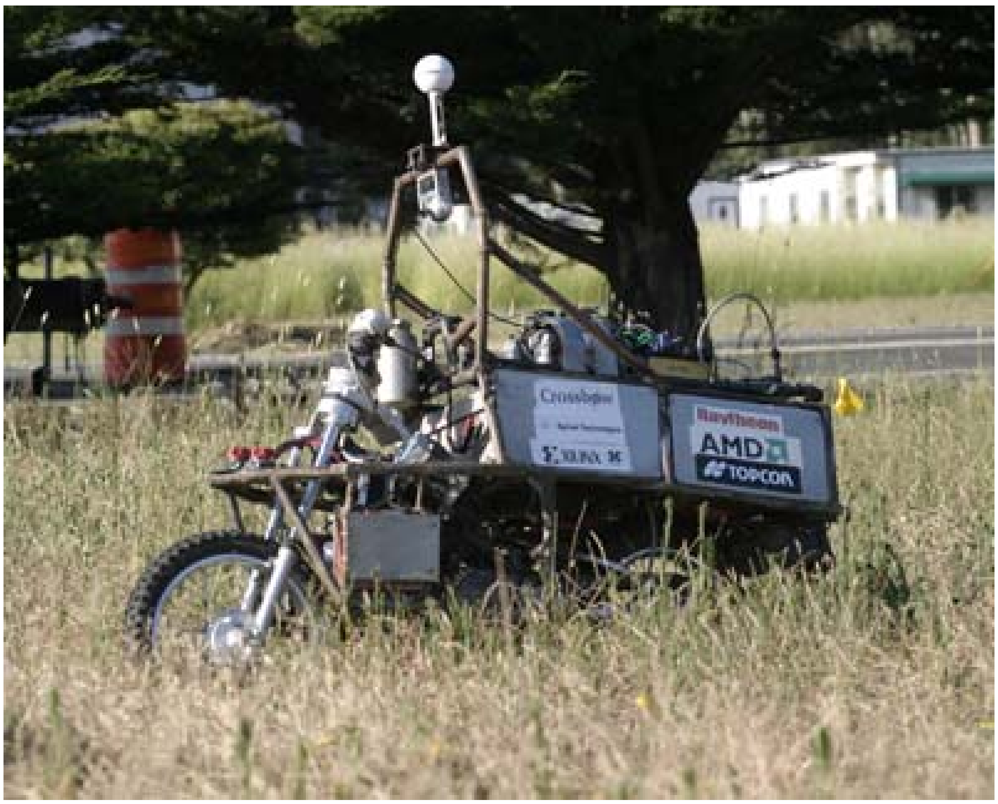
Autonomous Motorcycle Platform and Navigation – Blue Team DARPA Grand Challenge 2005



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Abstract – To successfully navigate the 2005 DARPA Grand Challenge (DGC05) route we built four key innovations: custom Inertial Angle Sensor (IAS), Learning Dynamic Stabilization Controller (LDSC), Stabilized Sensor Platform (SSP) and combined stereo vision with color road following.

Our single axis IAS is capable of 100KHz update rate with a resolution of 0.02 degrees. It is used for vehicle and gimbal pose estimation feedback into our LDSC and SSP.

Our environment sensing has both a reactive (color road follower) and a planning component (stereo vision), enabling it to navigate an open road safely while safely reacting to avoid obstacles.

1. Introduction

1.1 Motivation - Autonomous vehicles are typically designed to be used in environments that are dangerous, dirty and/or dull. However, the most dangerous and dirty applications are located in remote, narrow areas and require high-precision mobility. Foreign mountainous regions and urban situations are two prominent examples.

The percentage of this terrain that is accessible by a commercial 4x4 is small in comparison to the percentage of the terrain that is accessible to a motorcycle rider.

Figure 1. Ghostrider, our autonomous vehicle platform

Four wheeled vehicles which possess the off road capability that is needed for use in dangerous Reconnaissance, Surveillance and

Target Acquisition (RSTA) scenarios are often too large and heavy to be deployed quickly.

To our knowledge there are however no existing autonomous or tele-operated motorcycles. We seek to demonstrate the feasibility and showcase the advantages the platform possesses.

Figure 2. Dangerous, remote terrain

1.2 Team – Our team is composed of two groups one based in Berkeley, CA and one in College Station, TX. Vehicle and hardware development, stability testing, Global Positioning System (GPS) navigation and 3D vision is conducted at the Berkeley site while color road detection is done in College Station, TX.

The Berkeley group has seven (four graduate level and three undergraduates) core team members working between 10-80 hours a week each.

The College Station group has one core graduate student and one faculty advisor.

1.3 Related Work – Our vehicle draws upon the work of many, most notably that of Vittore Cossalter's "Motorcycle Dynamics", Neil Getz's "Dynamic Inversion of Nonlinear Maps with Application to Nonlinear Control and Robotics", Alonzo Kelly's "Minimum Throughput Adaptive Perception for High Speed Mobility" and Andrew Ng's "Inverse Reinforcement Learning".

2. Vehicle Description

2.1 Mechanical Setup – Our vehicle is a commercially available off-road motorcycle with a <100cc engine with automatic clutch aimed at riders weighing less than 150lbs (rough weight of electronics is 100lbs.). We run the vehicle in second gear which gives us enough climbing power to go up a 30 degree slope and provides us with a maximum speed of 40MPH. Substantial modifications were made to accommodate the electronics, power requirements and SSP.

Rationale for using a motorcycle for the DGC05 is that the added complexity stemming from need to provide dynamic stabilization is out weighed by the advantages gained from a narrower profile. Computing platforms and current technology are well suited for controlling unstable systems dynamically, but are not good at perceiving their environment. On the simplest level, a motorcycle effectively widens a traversable path by 3 feet on each side compared to the traversable path of a commercial 4x4.

For starting, pausing and recovering from a crash we integrated two screw jacks that push on arms on each side of the vehicle to pick it back up in three seconds.

All power is 24VDC, produced by engine and is stored in sealed lead acid batteries.

2.2 System Architecture - Our system architecture revolves around our environment sensing platform. Our GPS unit is used only for long range navigation, giving precedence to our vision system. In the event of loss of localization, the vehicle will keep operating based on the environmental sensors to find an appropriate road and follow it.

We use gigabit Ethernet as the communication layer for each component. There are two networks on the vehicle one dedicated for vision imagery transmission, and one for control and navigation.

Sensors feed into a custom built signal conditioning board then to a Field Programmable Gate Array (FPGA) (xilinx Vertex 2e on Calinx board) sensor hub with hardware filtering and hardware network stack. Sensor (GPS, IMU, accelerometer, FOG, IAS and encoders) data is broadcast over Ethernet (UDP) on the control network. This gives every PC onboard easy access to all information and simplifies data logging.

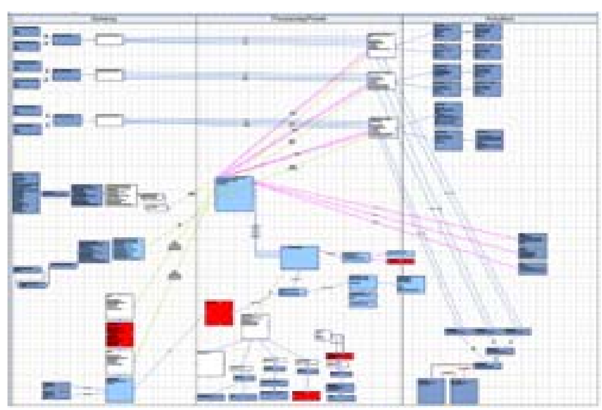


Figure 3 System architecture of all the components on the vehicle

Stability is performed by an embedded PC with an AMD Geode NX1500 1GHz Processor. Vision processing and navigation is performed on a Supermicro SuperServer with two AMD Opteron Dual Core 2.2GHz processors.

2.3.1 Controls Description - Stabilization is achieved by rapidly monitoring the vehicle's pose, speed and steering angle, using our custom built IAS (100KHz), speed and terrain static friction. A model of the vehicle's response is constantly being updated (100Hz) with feedback from the controller to minimize the error in vehicle motion.

There are 15 forces that constantly act on a motorcycle while in motion on semi-smooth ground (no jumps, deep sand, or ice). Only two are actuated inputs while 13 need to be controlled.

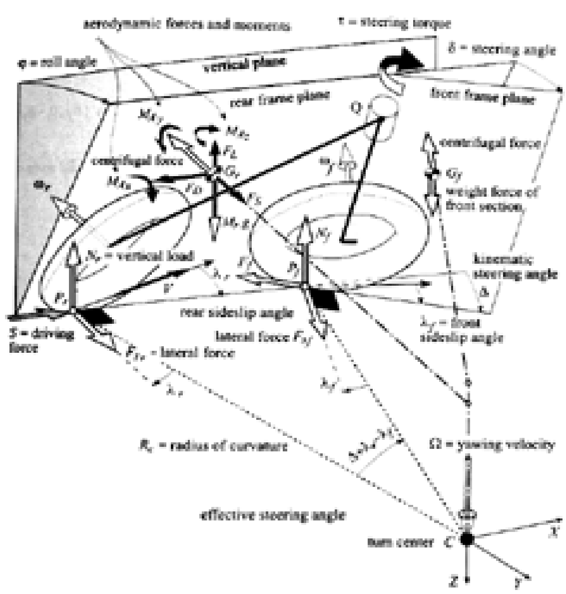


Figure 4. Forces acting on a simplified motorcycle in motion, based off of "Motorcycle Dynamics", Vittore Cossalter

Controlling the vehicle was a major delay in the project. Initially a fuzzy logic controller was designed to control the vehicle, but its complexity made it impossible to tune. Simple stability was easy to achieve using a Proportional Integral Differential (PID) controller. However, to get the vehicle to respond precisely to requested inputs required more modeling and simulation.

We integrated three IAS along with three fiber optic gyros, three accelerometers and FPGA hardware into a package that enables us to measure vehicle orientation at 100KHz. This sensor enables us to dynamically stabilize our vehicle at speeds of excess 30MPH.

2.3.1.1 Fuzzy Logic Controller – To facilitate the development of the stability controller, a fuzzy logic controller was based off of team member's intuition on how the vehicle should behave. The controller had 125 parameters and worked well at speeds of 3MPH to 6MPH. Tuning the controller to work at speeds of higher than 6MPH was too complex to try by hand and we did not want to build a simulator for the controller before getting better results.

2.3.1.2 PID Controller – We devised a simple nested PID controller in an attempt to improve the range of stability and control direction of the vehicle.

Stability range was immediately improved and directional control worked great on concrete or asphalt. Changes of surface properties (during a turn) were not accounted for and the vehicle was not as responsive on a course with different surface types (grass, sand).

It then became apparent that the integral term was extensively used to correct for roll angle error and steering angle error when the parameters were incorrect. This became evident as we damaged the front of the vehicle and it no longer steered straight initially but still stabilized.

Integral gain allowed the vehicle to stabilize well given physical damage, but contributed “sluggishness” (addition of a latency function) to the direction control. The uncertain latency in turn adversely affected the vehicle navigation.

Figure 4. Typical damage from crash during testing

While it is possible to compensate the initial vehicle parameters (adjusting them to match the pre-damaged values) to minimize the need for integral gain, we decided to modify the controller so that it may detect its own errors and correct them in run time. Modifying the controller in run-time would allow us to account for surface changes and learning/refining of parameters.

2.3.1.3 Reinforcement Learning -

The process we followed for converting our PID controller to a run-time reinforcement learned controller is as follows:

a) Created a stochastic model of the full vehicle dynamics

b) Seeded the control parameters with the best PID values we collected

c) Bounded the range for each parameter (with substantial ranges) to improve the rate of convergence and ensure minimum vehicle performance

d) Conducted offline reinforcement learning

e) Implemented new controller with learned parameters

f) 50 miles of testing with fixed parameters

g) Implemented run-time learning model

h) Conduct testing (50 miles to date)

Parameters have been seen to adjust substantially during the course of a run, but seem to be correlated to the surface properties and changes of direction in the requested course. Comparing the learned fixed parameter runs to the run-time learning parameter runs; the vehicle performance is significantly greater (as measured by ability of vehicle to follow a requested motion within small tolerances).

Figure 5. Testing of ability to run on bumpy terrain

Figure 6. Testing of ability to run on bumpy terrain

Figure 7. Typical steering offset causing crash

This seems to point to the fact that we are able to dynamically detect surface properties (bumps, sand, wind) and changes in physical characteristics of the vehicle during a run (tire pressure, steering offset, sensor offset, equipment vibration). Additional data is considered team proprietary.

2.3.2 Result - Dynamically controlled at 1KHz our motorcycle is stabilized to the ability of an amateur human rider. It seems much better at dealing with collisions, vegetation and recovering from bad situations (extreme roll angle). The controller is not as good as a human in situations were changing the vehicle's pose without steering would be beneficial such as when airborne. This can be addressed by the addition of a Control Moment Gyroscope (CMG), which would allow us to keep the vehicle vertical while standing still.

3. Vehicle Controller – We have integrated all of the required electronics into a small (9" x 8" x 4") rugged box designed to meet MIL-C-5015 and IP65 specs. Included in the box are: two AMD Geode NX1500 embedded PCs, Xilinx Spartan 3 FPGA motor controllers, brushless amplifiers, three axis IAS setup, sensor hub FPGA and status LCD.

Figure 8. Open LDSC with exposed wiring

This box is designed to be suitable for controlling almost any vehicle as it is capable of controlling several motors at substantial torques as well as having Gigabit Ethernet connectivity, 8 RS232 inputs and 20 high power relays (10 mechanical, 10 solid-state).

The LDSC runs our run-time learning controller for both autonomous and non-autonomous mode. The vehicle can then be run in non-autonomous mode tethered via Ethernet. Normally non-autonomous movement is done by pushing the vehicle while running the navigation control.

The LDSC is programmed to allow the vehicle to cross LBO's as the environmental sensing deems necessary. However, excursion from LBO by more than 33 feet (10 meters) will cause the vehicle to increase GPS navigation weight forcing it back on to the course. An excursion of 66 feet (20 meters) will cause the vehicle to stop and disable itself (for safety reasons).

4. Stabilized Sensor Platform Gimbal (SSP) – Navigating an autonomous vehicle requires accurate feedback from sensors about the surrounding environment. Vehicle movement over unstructured terrain causes orientation errors in the vehicle's sensors. The accurate pointing and orientation of the sensors is critical in forming a coherent picture of the environment. To stabilize our sensor package, we have built a gimbal and a controller that operate at 12K Hz to stabilize rotational errors down to 0.2 degrees. High precision, high accuracy harmonic gearing is used in the actuators of the SSP. The SSP uses HD Systems FHA family actuators with 50-1 reductions.

Figure 9. Image of beta testing our SSP

The SSP does not stabilize translational movement (typically less than 6 inches for our vehicle).

The SSP is mounted in the front of our vehicle over the front wheel to minimize debris obstructing the sensors. The performance and frequency response of our SSP has not been characterized to date. Further information will be available online at www.laraison.com as tests are conducted.

5. Processing – Our vehicle uses several types of processing onboard for performing stability, navigation and sensing tasks.

5.1 Microprocessors – We have six CPU cores available for processing on the vehicle. Four cores are dedicated to vision processing. They are located on a Supermicro SuperServer dual CPU dual-core AMD Opteron 275, each operating at 2.2GHz. Of the four vision cores, three are dedicated to 3D reconstruction and one for color road detection.

Figure 10. Supermicro SuperServer Dual Code AMD Opteron

The other two cores are AMD Geode NX1500 operating at 1GHz running two embedded pc's inside the LDSC and SSP.

5.2 FPGAs – We have five Xilinx FPGAs on board our vehicle. A Xilinx Vertex 2E handles all of our sensor watchdog, format conversion and Ethernet (UDP) distribution.

Two identical AlphaData ADM-XP with Xilinx Vertex 2 Pro 100 each processes black and white image by performing filtering and transformations to correct image distortion before computing disparity.

Two Xilinx Spartan 3 are used to perform high speed motion control for steering and SSP as well as processing encoder and hall sensors for brushless HD Systems FHA actuators.

5.3 Signal Interfacing – Integrated into our LDSC is a signal conditioning board that enables the 3.3V tolerant Xilinx Vertex 2E to communicate at RS-232/422/485 levels with sensors.

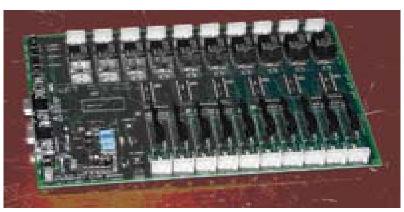


Figure 11. E-stop safety receiver interface board

To simplify interfacing with the DGCRX system we built a custom board that contains a small ATMEL microcontroller. The microcontroller interfaces with the safety receiver and communicates to the sensor hub FPGA. The safety receive interface board contains 10 mechanical relays and 10 solid state relays.

5.4 Complex Programmable Logic Devices (CPLD) – Our vehicle's starting arms are controlled by MOSFETS switched by Xilinx CPLDs.

6. Navigation

6.1 Localization – Our vehicle testing has shown that we do not benefit from DGPS while running. DGPS is unreliable and causes jumps in our desired direction and position when quality of fix occurs. Jumps in our position or orientation are not favorable to our navigation algorithm at this point.

We have selected a unit manufactured by Topcon Positioning Systems called MapHP which can receive both the Omnistar VBS (claim of sub meter, which we occasionally see) and HP (claim of 5 centimeter, which we have never seen) correction service that tracks both GPS and GLObal NAvigation Satellite System (GLONASS), Russian version of US GPS, satellites. Typical coverage for us is 10 GPS and 4 GLONASS satellites.

Figure 12. Topcon Map HP receiver on top of Ghostrider during endurance test in Nevada

Both DGPS (VBS and HP) correction services are activated but corrections are received about 10% of any given run on a realistic DGC05 course (contains foliage, canyon and urban canyon features).

We use no map data.

6.2 Navigating principal – Environmental sensors are the most important piece of equipment for successfully navigating the DGC05. Our vehicle uses GPS as a sensor providing guidance, not relying on it to navigate along a path. Vision provides what the vehicle thinks is the most likely traversable path weighted by desired direction. Direction information is not needed for instantaneous feedback regarding vehicle positioning on the path. We assume there is a feasible path and vision will always output a direction.

7. Sensing

7.1 Equipment – Our vehicle uses only cameras as the sole means for environment detection. The cameras we use are manufactured by Cognex. Two different types of cameras are used:

a) Cognex InSight 5304 - Black and white 8-bit, single CCD, 1600x1200, 15fps, Ethernet interface with onboard computation capabilities.

b) Cognex InSight 5400C – Color, 24-bit, 3CCD, 64x480, 60fps, Ethernet interface, with onboard computation capabilities.

Figure 13. Image of camera setup

7.2 Road detection – Our vehicle's road detection software is based on a mixture of published well known algorithms. Key innovation was identifying the proper selection to implement. The selection criteria were heavily biased towards performance in terrain similar to the Mojave

Desert. Color and texture information are essential to the performance of the system.

Figure 14. Image of favorable color texture

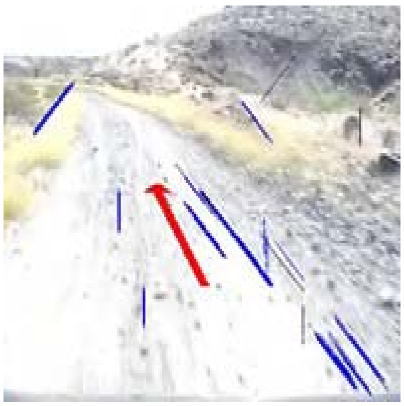
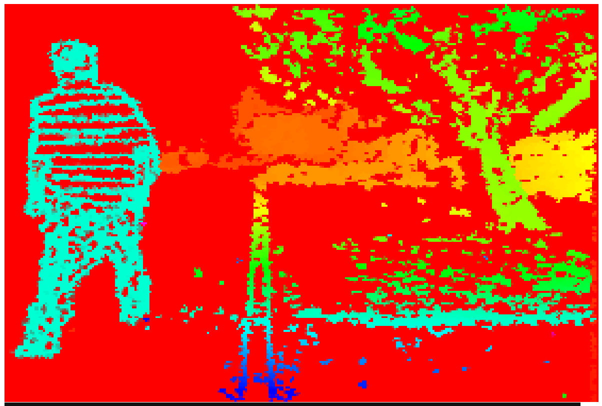


Figure 15. Image of perceived road direction

7.3 3D Reconstruction – Based off of the best published disparity algorithm we could find. Key innovation was reproducing the results and generating optimizations for real-time computation. System operates at 4 Hz, has a base line of 8 inches and range of 25 meters. Obstacles are easy to pick up. Road, which lacks texture, is not as evident by the images below.



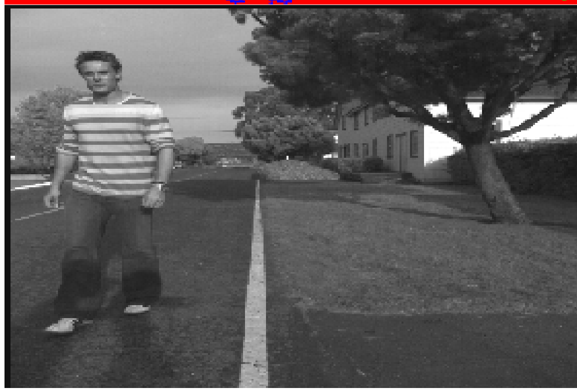


Figure 16. Image of 3D reconstruction with high rejection, not missing data for asphalt. Color represents distance

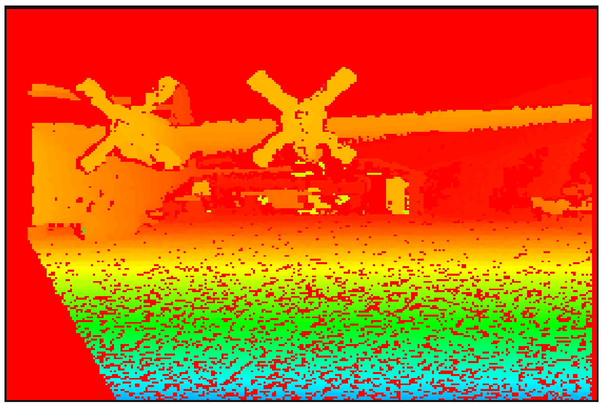


Figure 17. Image of 3D reconstruction with low rejection note invalid background measurements. Color represents distance

Purpose is to detect obstacle and identify forward part to take in the following 500ms.

7.4 Arbitration – The two visions systems are complementary in that they both work well at one task that the other does not. Color road detection has difficulty identifying obstacles vs. changes in road color while 3D can detect obstacles but has hard time picking up asphalt roads or smooth trails.

Currently our vehicle performs using only one of the two sensing schemes. The reason for this is that to-date, we have not implemented the Unscented Kalman Filtering UKF that we wish to use for fusing the two sensing inputs.

The reason for using a UKF is that the estimated state and covariance are augmented with the mean and covariance of the process noise, which in this case is the rate of error of our sensing scheme, a parameter easy to measure but difficult to characterize.

8 Testing – We view testing as the most important part of our team's approach to DGC05. Software system tests in laboratory settings were kept to a minimum to maximize the time and number of trials under real world conditions. Hardware was integrated as early as possible to have weak components break so that replacement components could be found. Wiring was a key factor in ensuring quality. We spent a significant portion of our time testing the wiring setup.

Figure 18. Testing of self-righting arms

Once the vehicle is operational, it goes out for testing twice every week. The vehicle has gone through two full revisions (rebuilt from engine up) in the year and a half before DGC05.

Figure 19. Alternative chassis version

Figure 20. Testing the operation of Ghostrider "rubber-side-up"

Figure 21. Accidental "washing" of Ghostrider

In total there have been over 800 runs of the vehicles with a total mileage of 400 miles, most of it in 10+ mile runs. Our testing grounds have been at Lake Winnemucca in Nevada, which we found as a suitable DGC04 course replacement.

9. Acknowledgements – Our vehicle's entry into the DGC05 would not have been possible without the generous contributions from the following organizations: AMD, Agilent, Alpha Data, Berkeley College of Engineering, Cognex, Crossbow Technologies, HD Systems, LaRaison, Memtech, Topcon, Xilinx.

Special thanks go to the following individuals who have help us in the development and testing of the vehicle: Sing Yiu Cheung, David Garmire, Jae Lee, Victor Colborn, Ognen Stojanovski, Jack Tzeng, Steve Lhi, Jingang Yi, Ken Goldberg, Karl Hedrick, Richard Newton.

10. Future Work – We intend to fully characterize the motorcycle platform using our LDSC. With that capability we will be able to develop a high performance data acquisition platform for motorcycle testing (suspension, tires and handling) and racing. In addition we intend to commercialize our IAS (specifications are 0.02 degree resolution, 100KHz update rate, 1 degree / hour bias, very stable over wide temperature range (-10C to 55C), target price $1,999). We also intend of making our SSP and its motion controller available for a variety of applications.